Hydrodynamic Models of AGN Feedback on Cooling Cluster Gas

Galaxy and Black Hole Evolution: Towards a Unified View

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11/30/2007

Outline

Cooling Clusters and AGN jets

- Background
  - Cooling Flows and Galaxy Formation
  - AGN jets and Feedback
- 2D Hydro Models
- 3D Hydro Models
- Precessing Jet Models
- Conduction and other physics

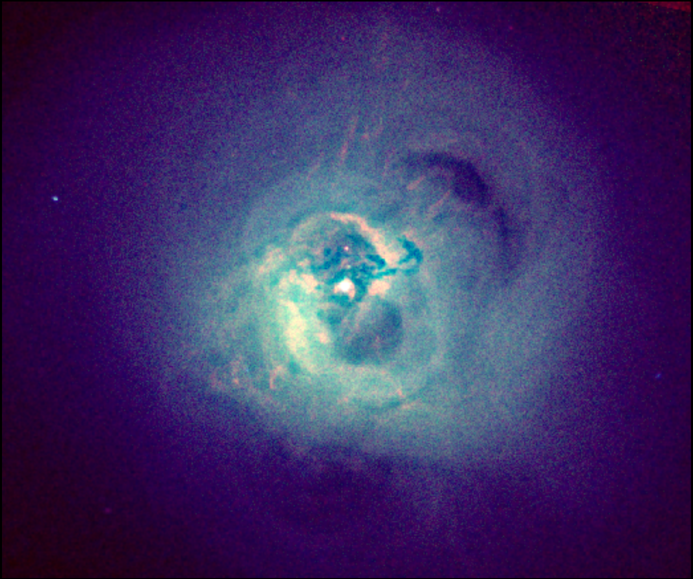
Background

- The Intracluster Medium (ICM) in rich relaxed clusters is cooling, primarily in X-ray.
- Central cooling times shorter than the age of the cluster, but strong observational limits on the amount of cool gas.
- Nothing below $\sim \frac{1}{3} T_{virial}$ (from XMM-Newton observations).
- This is the classic Cooling Flow Problem.
- This is also same as the cutoff in the high end galaxy luminosity function.

Background – AGN jets

- Powerful, with right energy to balance cooling (but see Bîrzan et al. 2004 for possible problems with this idea).
- Often in cluster centers, just where heating is needed.
- But how exactly does this heating work?
- Is the efficiency enough and is the heating spatially distributed properly?

Evidence for Interaction



Perseus A, Fabian et al. 2005

Our Work

Use models to assess the efficiency and spatial distribution of heating from AGN jets under the assumption of ideal hydrodynamics.

- Initially cluster is spherically symmetric, hydrostatic, ball of gas.
- β-model atmosphere with static potential.
- Supersonic, underdense jet injected on the inner boundary.
- Radiative Cooling (in the 3D models).

Modified Public Hydro Code

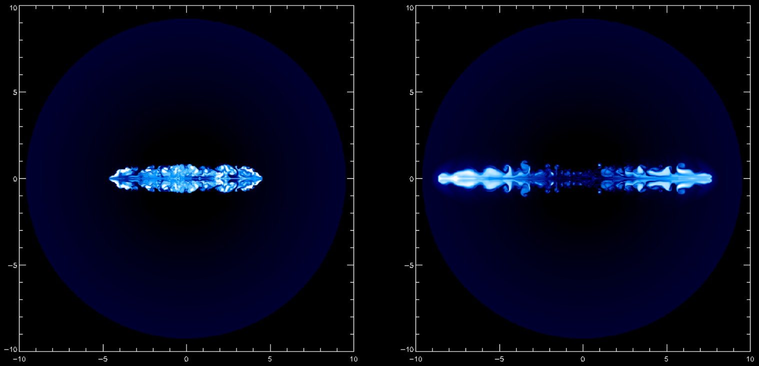
- Modified and updated version of FORTRAN 77 NCSA release.
- ZEUS-MP v1.5.13
- http://www.astro.umd.edu/~vernaleo/zeusmp.html

2D Models

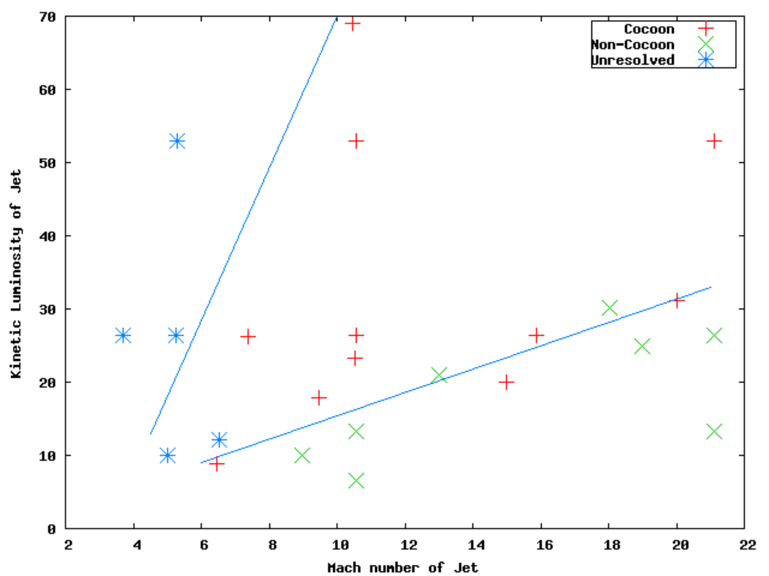
We can cheaply study a wide range of jet parameters in 2D (axisymmetric) models.

- High resolution.
- Can compare evolution of jet inflated structures ("cocoons") and energetics with jet parameters.
- See Vernaleo & Reynolds 2007.

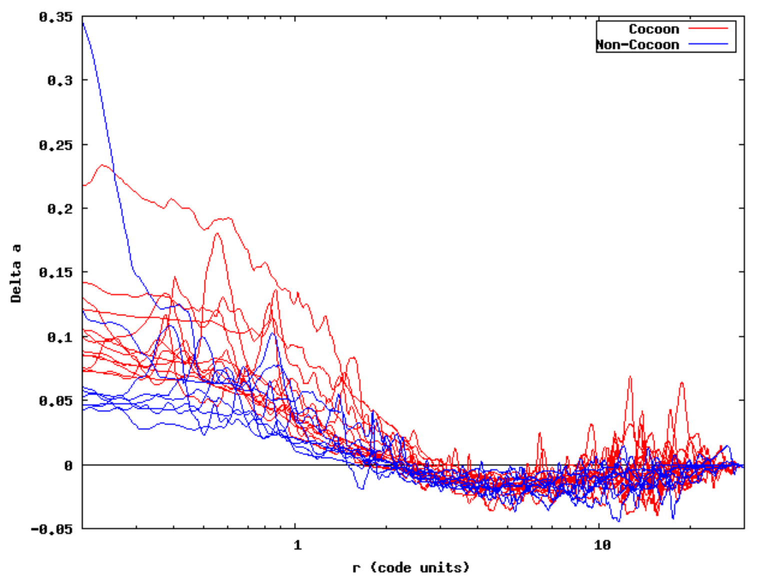
Cocoon or Non-Cocoon?



Separate Regions of Parameter Space

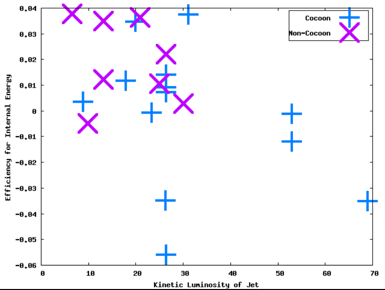


Total Entropy Change vs. Radius

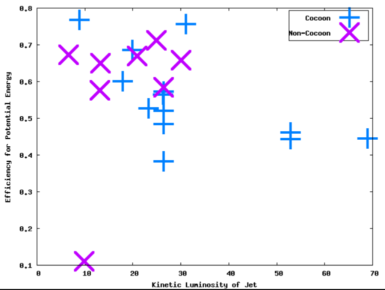


Energy efficiencies

Internal



Potential

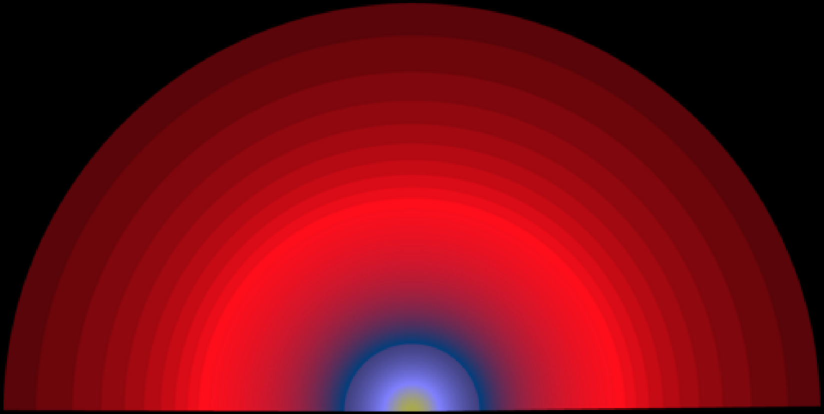


Efficient at thermalizing energy, but most of the energy goes to “puffing up” the atmosphere.

2D Summary

- Jet inflated structures fall into two morphological classes.
- Cocoons efficient at changing central entropy.
- Jets efficient at thermalizing energy, but it mostly goes into potential.

3D Models: Single Jet Burst – Density



Feedback Scenarios

Can we close the feedback loop by coupling the jets to the cooling ICM?

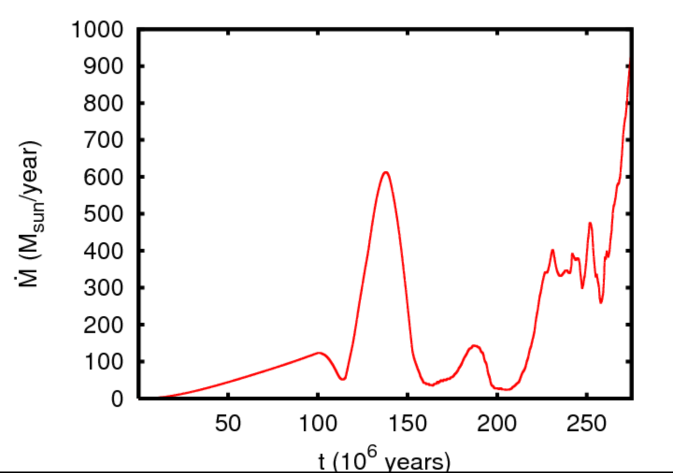
- Single Jet.
- Inject a jet with $L_{kin} \propto \dot{M}$.
- Delayed Feedback.
- This is getting close to feedback from first principles.
- See Vernaleo & Reynolds 2006.

Delayed Feedback

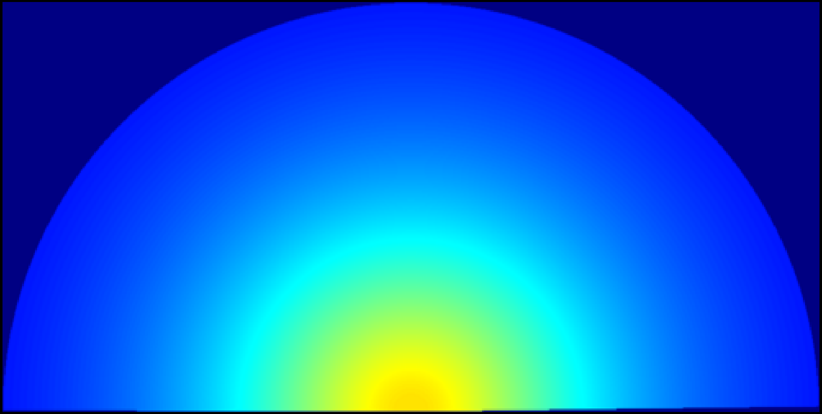
$$v_{jet} = \left(\frac{2\eta \dot{M} c^2}{A\rho} \right)^{\frac{1}{3}}$$

We introduce a delay (100 Myrs which is the dynamical time of the cluster center) between v_{jet} and $\dot{M}$.

Delayed Feedback – Mass accretion on inner boundary



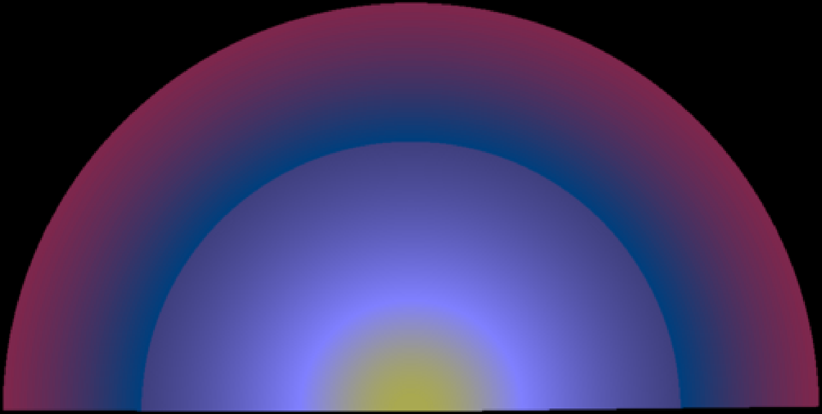
Channel Formation and the Failure Mode of Feedback Models



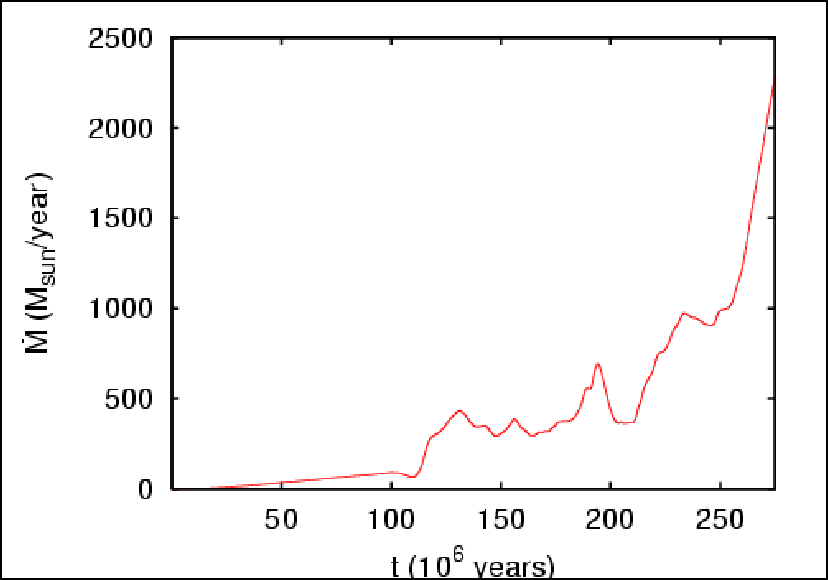
Precessing jets

- Vary the jet axis.
- This will break the symmetry that caused the channels in our previous work.
- Some evidence for this in Perseus (Dunn et al. 2006).

Precessing Jet – Density slice



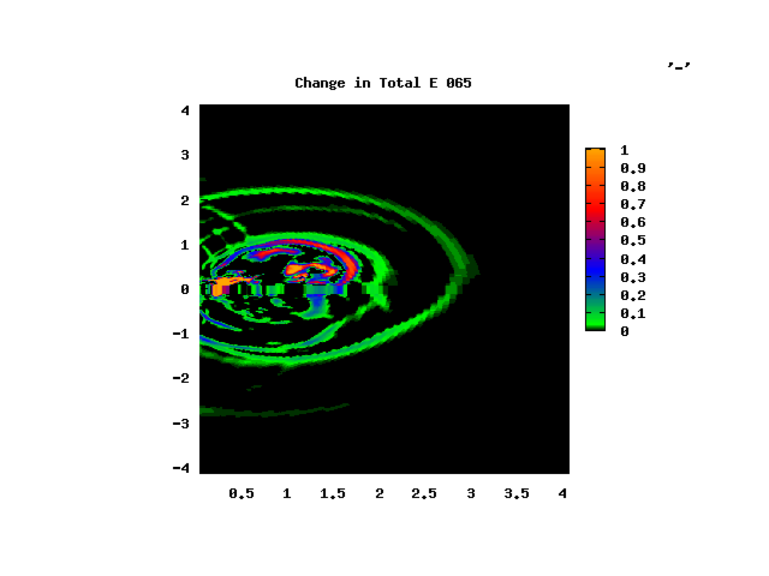
Precessing Jet – Mass accretion on inner boundary



Still no stable solution.

- Basically get the same result for all $\dot{M}$ based feedback cases.
- Even without channel formation, cooling proceeds.
- Jet would need to cover entire range of angles in less than cooling time for central gas.
  - Seems unlikely.
- Hard to couple (powerful) jets to ICM core gas in ideal hydro.
- Jet does excite lots of sound waves and weak shocks, seemingly more than a fixed-axis jet.

Waves and weak shocks



Possible Solutions

- Need something to capture sound wave energy.
- In ideal hydro, too much of the AGN power is lost in these waves that cannot dissipate.
- We need other plasma processes in the gas to do this.

ICM Physics

- Viscosity:
  - Intact bubbles in Perseus show some evidence for this.
  - Reynolds et al., 2005 did some simulations of this.
- Magnetic Fields?
- Thermal Conduction
  - Conduction at some fraction of Spitzer value.
  - Bring heat from outer regions in.
  - Dissipate wave energy.
  - If conduction can help us tap the wave energy before it leaves the core, a stable balance should be possible (See Fabian et al. 2005).

Conclusions

- 2D models shows us two populations of sources based on jet parameters.
- Jets efficiently thermalize their energy and it goes mostly into the potential.
- In 3D models, we are unable to balance cooling by coupling jet power to cooling gas.
- Jets excite lots of sound waves and weak shocks, but that energy is lost.
- Possible solution in thermal conduction.